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A REVIEW OF FLUIDIZED BED COMBUSTION
TECHNOLOGY IN THE UNITED STATES

R. P. Krishnan C. S. Daw
J. E. Jones Jr.

Oak Ridge National Laboratory*
Oak Ridge, Tennessee 37831
USA

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INTRODUCTION

The United States (U.S.) initiated work in fluidized bed combustion (FBC) in the mid-1960s, with primary emphasis on industrial applications. With passage of the Clean Air Act in 1970, the environmental benefits of the technology soon attracted interest. This provided the impetus for expanded effort focused on the reduced NO_x emissions resulting from lower combustion temperature and SO_2 capture by means of chemical reaction with limestone or dolomite in the fluidized bed. The oil embargo in 1973 further stimulated interest in FBC technology.

Several manufacturers presently offer atmospheric fluidized bed combustion (AFBC) and circulating fluidized bed combustion (CFBC) units for industrial application in the United States. However, FBC for electric power generation remains in the development and demonstration phase. The Tennessee Valley Authority (TVA) and Electric Power Research Institute (EPRI) are operating a 20-MW AFBC utility pilot plant and are proceeding with plans for a 160-MW(e) demonstration plant with other participants. Research has been under way on pressurized fluidized bed combustion (PFBC) at Grimethorpe in South Yorkshire, England, and within the United States at the Curtiss-Wright Pilot Plant, and at other smaller test facilities. An emerging turbocharged PFBC concept will likely stimulate more near-term interest in PFBC technology for both industrial and utility applications.

The major U.S. programs and test facilities are described herein; remaining technical uncertainties are discussed, and the future outlook for the technology is assessed.

DESCRIPTION OF FLUIDIZED BED COMBUSTION PROGRAMS AND FACILITIES IN THE UNITED STATES

The information presented here has been obtained from current literature and from site visits made by the authors in 1983. Our intent is to provide a concise summary of the accomplishments to date in atmospheric, pressurized, and circulating fluidized bed technology in the United States.

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Atmospheric Fluidized Bed Combustion Program

Table 1 describes some of the major AFBC facilities. A brief summary of these programs is contained in the following section.

TVA 20-MW AFBC Pilot Plant [1,2]. TVA's 20-MW AFBC Pilot Plant is the largest and most important AFBC facility in the United States. Construction began at the Shawnee Steam Plant near Paducah, Kentucky, in April of 1980. Testing and operation began in mid-1982. The boiler and associated equipment were designed and built by Babcock & Wilcox Company as the prime contractor with Stone and Webster Engineering Corporation as subcontractor. Coal and limestone handling facilities were designed and built by TVA. The pilot plant was funded by TVA and federal appropriations. The test program and operation of the facility are funded jointly by EPRI and TVA.

The pilot plant is designed to be capable of testing a range of operating conditions, load control techniques, recycle, and solids feeding strategies. It is highly instrumented to provide sufficient information for detailed heat and mass balances and fundamental studies of AFBC performance phenomena.

The boiler, shown in Fig. 1, is a pump-assisted circulation drum-type unit producing superheated steam at a nominal 16.6 MPa and 539°C. The bed area is 3.7 m wide by 7.3 m long with a waterwall tube enclosure. The active bed is

5.5 m long, yielding an area of 20 m². This section is further divided into four operating compartments that contain boiling and superheating heat transfer surface. The remaining 1.8 m of length contain no submerged heat transfer surface and is designated as the start-up compartment. The enclosure walls also contain a number of sampling ports to permit the determination of gas composition throughout the unit and special instrumentation to determine the heat transfer rate to the wall tubes.

The furnace floor, which serves as the air distributor plate for the fluidized bed, is made from tubes with membranes welded between the tubes. The waterwall tubes are tied into the furnace floor tubes enabling the distributor plate to be water-cooled and to serve as a steam generating surface. The distributor plate is covered with a 5-cm-thick layer of refractory material. Approximately 2000 bubble caps supply combustion and fluidizing air. There are three types of bubble caps. Each one provides different air flow and is located in such a way that solids mixing is promoted and localized reducing zones are eliminated. Each of the operating compartments has three underbed coal/limestone feed points and one bed solids drain. One underbed fly ash recycle feed point is located at each of the three boundaries between operating compartments.

FIGURE 1. TVA 20-MW AFBC pilot-plant boiler

TABLE 1. Summary of the design specifications for the major U.S. AFBC facilities

Site	Bed dimensions/ feed points	Nominal bed conditions	Fuel	Sorbent	Heat-transfer/ working fluid
TVA AFB Electric Utility Pilot Plant	Main bed - 3.6 m x 5.5 m (4 compartments). Start-up bed - 3.6 m x 1.9 m. 3 fuel injection points in each compartment. 8 fuel injection points in start-up bed.	Temp. = 840 °C. Sup. Vel. = 1.2 to 3.6 m/s. Active bed ht. = 1.2 m. Freeboard ht. = 4.6 m. Underbed pneumatic fly ash recycle.	Kentucky #9. 4 - 4.5 wt % S. 0.64 cm x 0. 5440 kg/h. Underbed pneumatic and overbed stoker feed.	Reed limestone. 0.32 x 0. Ca/S = 1.5 - 4.0. Under and overbed feed (mixed with coal).	Closed cycle/steam. Economizer, convection tubes, waterwalls, in-bed tubes. Superheated steam condensed in air-cooled condenser. Rate = 50,800 kg/h. Steam T = 540°C. Steam P = 16,550 kPa (abs).
B&W - EPRI Research AFB Boiler	1.8 m x 1.8 m total. (4 compartments). 5 fuel injection points.	Temp. = 790° - 900°C. Sup. Vel. = 1.2 - 4.3 m/s. Active bed ht. = 0.9 - 1.8 m. Freeboard ht. = 5.5 m. Underbed pneumatic fly ash recycle.	Kentucky #9, lignite, other bituminous coals. 4 - 4.5 wt % S. 0.64 cm x 0. 840 kg/h. Underbed pneumatic and overbed stoker feed.	Lowellville and Reed limestone. 0.32 cm x 0. Ca/S = 1.5 - 4.0. Underbed pneumatic and overbed stoker feed (mixed with coal).	Closed cycle/steam. Economizer, in-bed tubes. Rate = 900 - 4500 kg/h. Steam P = 1140 kPa (abs). Steam T = 185° - 540°C.
Great Lakes Naval Station AFB Boiler	2.4 m x 5.3 m total. (6 compartments). 8 fuel injection points.	Temp. = 800° - 815°C. Sup. Vel. = 2.1 m/s. Active bed ht. = 0.9 m. Freeboard ht. = 2.1 m. Underbed pneumatic fly ash recycle.	Illinois #6. 3.5 wt % S. 0.64 cm x 0. 3050 kg/h. Underbed pneumatic feed.	Limestone. 0.48 cm x 0. Ca/S = 2 - 4. Underbed pneumatic feed (mixed with coal).	Closed cycle/steam, convection tubes, in-bed tubes, water- walls, economizer. Rate = 22,700 kg/h. Steam P = 2590 kPa (abs). Steam T = 290°C. Steam to station heating system.
Georgetown University AFB Demonstration Boiler	1.7 m x 5.9 m total. (2 compartments). 2 fuel injection points.	Temp. = 840° - 865 °C. Sup. Vel. = 1.8 - 2.4 m/s. Active bed ht. = 1.4 m. Freeboard ht. = 3.4 m. Side pneumatic injection fly ash recycle.	Eastern bituminous. 3 - 3.5 wt % S. 2.5 cm x 0. 4340 kg/h. Overbed stoker feed.	Limestone. 0.32 cm x 0.10 cm. Ca/S = 3.0. In-bed gravity feed.	Closed cycle/steam. Economizer, convection tubes, waterwalls, in-bed tubes. Rate = 45,400 kg/h. Steam P = 2000 - 4400 kPa (abs). Saturated steam to University heating system.
East Stroudsburg State College AFB Boiler	6.7 m x 1.6 m total. (6 compartments). 4 fuel injection points and 2 for fuel/sorbent mixture.	Temp. = 870°C. Sup. Vel. = 1.8 m/s. Active bed ht. = 1.0 m. Freeboard ht. = 4.0 m. In-bed gravity fly ash recycle. Turndown 3/1.	Anthracite culm. 0.5 wt % S. 0.33 cm x 0. 3200 kg/h. Side injection pneumatic feed.	Limestone. 0.64 cm x 0. Ca/S = 2.6. Side injection pneumatic feed (mixed with coal).	Closed cycle/steam. Economizer, convection tubes, waterwalls, in-bed tubes. Rate = 18,200 kg/h. Steam P = 1240 kPa (abs). Saturated steam to college heating system.
Wilkes-Barre Industrial AFB Boiler	5.5 m x 4.3 m total. (1 compartment).	Temp. = 820°C. Sup. Vel. = 1.2 - 1.8 m/s. Active bed ht. = .9 - 1.1 m. Freeboard ht. = 2.7 m. In-bed pneumatic fly ash recycle.	Anthracite culm. 0.5 wt % S. 0.64 cm x 0. 7100 kg/h. Overbed stoker feed.	Limestone. Ca/S = 1 - 3. 0.32 cm x 0. Overbed gravity feed.	Closed cycle/steam, water- walls, convection section. Rate = 27,000 kg/h. Steam P = 965 kPa (abs). Saturated steam to industrial users.

Bed material is removed through five bed gravity drain nozzles into water-cooled screws. The cooled material is pneumatically transported to the disposal silo.

The flue gases pass through three cyclone collectors. Solids collected in the cyclone bins are fed to a hot material storage bin from where it is either recycled to the bed or pneumatically transported to silos. Flue gases from the cyclone separators pass through a baghouse. An electrostatic precipitator is installed in parallel with the baghouse for testing purposes.

The objectives of the pilot plant are to:

- Demonstrate acceptable long-term operation and performance,
- Develop and demonstrate automatic control and load following capability,
- Develop a data base for multiple fuel and sorbent types,
- Demonstrate environmental control capability,
- Develop the capability to specify and design auxiliary equipment, especially the coal, limestone, and recycle feed systems, and
- Test and evaluate materials of construction for the boiler and its auxiliaries.

Six operating campaigns over a 5-year period have been programmed beginning in March 1982:

1. Initial shakedown and operating experience,
2. Comparison of underbed and overbed coal/limestone feeding,
3. Demonstration of load control techniques,
4. Bed response to transient conditions,
5. Environmental assessment, and
6. Alternate fuels evaluation.

Campaign 1 was completed in March 1983. Campaign 2 was completed in May 1984. The pilot plant had operated roughly 6735 h at the end of Campaign 2. The longest uninterrupted coal feed run lasted 700 h in February 1984. Significant results to date are:

- From an operational standpoint, the overbed feed system proved to be very reliable with few mechanical problems. The underbed feed system experienced problems with plugging and erosion.
- Fines and rocks in the "as-received" coal made operation and testing extremely difficult with overbed feeding. It was necessary to wash the coal to complete the overbed tests.
- The Fuller-Kinyon recycle pump experienced several problems that limited the recycle capacity to 16,340 kg/h or a recycle ratio of 4 to 1 in terms of the pounds of coal fed.
- No appreciable erosion or corrosion was seen in the boiler.
- Combustion efficiency of 97% with a recycle ratio of 2 to 1 was obtained when feeding underbed or overbed with washed coal. With unwashed coal and overbed feedings, the combustion efficiency dropped to 92% for the same recycle ratio because of excessive elutriation.
- A 90% sulfur retention was achieved using underbed or overbed feed with washed coal at a Calcium to Sulfur ratio of 2 to 2.5 and recycle ratio 1.5 to 2.5.
- The NO_x ranged from 0.065 to 0.17 g/10⁶/J with recycle ratio of 2 to 2.5 for underbed feed. The values for overbed feed for the same condition were in the range of 0.11 to 0.24 g/10⁶/J. Heat transfer characteristics were comparable for the underbed and overbed feed system with washed coal. The overbed feed tests showed a higher heat release in the freeboard. Recycle showed a significant impact on the in-bed/freeboard heat release split.

Campaign 3 tests will commence in mid-June 1984.

Babcock & Wilcox/Electric Power Research Institute Atmospheric Fluidized Bed Combustor [3,4]. The Babcock & Wilcox (B&W) Company has built and is operating, under a program sponsored by EPRI and B&W, a 1.81×1.81 -m atmospheric fluidized bed combustion test facility at the B&W Alliance Research Center. The facility was designed to serve as an intermediate-scale unit to help bridge the gap between small bench-scale units and a demonstration-scale AFBC facility.

Construction of the facility was completed in September 1977, and shakedown tests were completed in April 1978. Since that time, approximately 13,000 h of testing have been logged at the facility, demonstrating the capability for long-term, steady state operation, with tests typically lasting from 300 to 500 h. Operation of the facility has resulted in several major technology, process, and hardware improvements. The operation has covered a range of superficial velocity from 1.5 m/s to 4.3 m/s with most of the operation being between 2.4 and 3.6 m/s. Two local bituminous coals — Ohio No. 6 and Pittsburgh No. 8 — have served as the primary fuels with brief periods of operation with lignite, oil, and petroleum coke. In support of the TVA 20-MW AFBC pilot plant, Kentucky No. 9 coal has recently been used as fuel.

Crushed and screened coal and limestone are fed from separate bunkers through separate weigh feeders into the common transport system. The mixed solids are pneumatically transported to a splitter where the feed stream is equally split into four separate lines that carry the coal and limestone into the combustor.

Combustion air, supplied by a forced draft fan, is heated in a steam coil air heater (normal operation) or a direct, gas-fired air heater (start-up operation) before it is divided into the four separate streams entering the four 0.91×0.91 -m windbox compartments. The modular design allows major test parameters such as bed temperature, superficial velocity, and excess air to be uncoupled to study the individual effects.

The air distributor is a bubble cap design with a refractory-lined floor. Bed discharge pipes are located in each corner of the distributor plate. The bed discharge valves are actuated when the pressure drop across the bed exceeds a preset value. Spent bed material is cooled and metered by an impact flowmeter prior to being discharged.

The furnace enclosure consists of an atmospheric pressure, plate-type water jacket with fire side refractory lining. The in-bed tube bank contains two sections cooled by high-pressure water and one section cooled by superheated steam. The convective tube bank is located 6.7 m above the distributor plate. It is composed of a boiling surface, completely separated from the in-bed boiling circuit.

Four cyclone dust separators are located downstream of the furnace exit. Material collected by the cyclones can be discarded or recycled. After flue gas exits the cyclones, it enters a baghouse and is then exhausted through the induced draft fan to the stack.

Testing has covered the following parameters:

- Single or multiple coal feed points;
- Fluidizing velocities of 1.2, 2.4, and 3.6 m/s;
- Different fuels (coals, lignite, petroleum coke, and oil);
- Different types of limestone;

- Two-stage combustion;
- Underbed and overbed fly ash recycle;
- Load turndown through bed slumping and velocity variations;
- Bed transient behavior at various load change conditions;
- Automatic load following system;
- Regrinding of spent bed material and recycling of reground material; and
- Freeboard reactions.

The results of these tests have been documented in several papers [5,6]. Some of the most significant findings are:

- The design of the fluidized bed combustor should be matched with the characteristics of the fuel and additive. Reactive fuels such as lignite and some of the sub-bituminous coals burn quite rapidly and efficiently without the need for recycle, whereas harder to burn fuels such as anthracite and petroleum coke need special design attention.
- Although it has been demonstrated that recycle operation improves combustion efficiency and sulfur retention, its effect on freeboard reactions, heat release rates in the bed and in the freeboard, and NO_x emissions still remain to be quantified.
- The performance of AFBCs in general seem to improve with scale as indicated by comparison of results in the B&W unit with results emerging from the TVA 20-MW pilot plant.
- Combustion efficiency on the order of 95% to 97% and sulfur retention of 90% at a Calcium/Sulfur ratio of 2.5 to 3.0 are achievable with recycle operation.
- NO_x emissions from the unit are of the order of $0.17 \text{ g}/10^6 \text{ J}$ of input.
- CO levels were around 200 ppm at 15% excess air.
- Metallurgical examination of the in-bed tubes has indicated that ferritic alloys are satisfactory up to a temperature of 510°C ; austenitic alloys are suitable above 510°C . Materials containing more than 25% nickel may be subject to very rapid corrosion.

Future testing in the B&W test facility will include operation of the unit with other fuels and specific tests in support of the TVA 20-MW Pilot Plant and the TVA 160-MW Demonstration Plant.

Department of Energy/Combustion Engineering (DOE/CE) Great Lakes Demonstration Facility [7,8]. The DOE/CE industrial AFBC is a 22,700-kg/h steam boiler located at the Great Lakes Naval Station near Chicago. Completed in the latter part of 1981, the plant has operated for a total of approximately 5200 h on high sulfur (3% to 4% S) Illinois coal. The longest continuous run lasted for 30 d. The final test run was concluded in May 1984.

Key features of the facility are its symmetrical shape to fit shipping clearances to rail transportation, compartmentalized zones in the bed to permit bed slumping to meet changing load demands, pneumatic underbed coal/sorbent feed, natural circulation steam flow, and provision for fly ash reinjection.

The major problems have been (1) erosion of the riser tubes in the convection pass because of improper design, (2) bowing of the superheater tube bundles, (3) undersized preheater resulting in heatup of the baghouse, (4) excessive solids carryover due to the short freeboard (2.1 m) necessary for rail shipment, (5) warping of the perforated distributed plate, and (5) plugging of the underbed feed system. These problems were corrected and the test program was completed as planned.

Some of the important lessons learned were (1) the need for a reliable underbed feed system for commercial units; (2) the need for sized and dried coal to reduce fuel feed problems; (3) the need to improve sorbent utilization; (4) the need for a better understanding of solids/gas mixing in the bed and in the freeboard; and (5) the importance of radiation on bed and freeboard heat duty.

Combustion Engineering is preparing a final project report to DOE. The Navy is in the process of dismantling the facility at this time.

Georgetown University Industrial Atmospheric Fluidized Bed Combustor [9,10]. The Georgetown University Industrial AFBC, sponsored by DOE and designed by Foster Wheeler, is rated at 45,500 kg/h steam. Plant start up was in the summer of 1979, and approximately 17,000 operating hours have been accumulated.

The facility is designed for natural circulation to generate saturated steam at pressures between 2 and 44 MPa. It contains two independently fired fluidized beds, each with a separate overbed stoker-spreader. Fly ash is reinjected to only one of the beds. Turndown ratios of up to 4 to 1 can be achieved. Limestone is fed by gravity at a single point in each bed. Light-off of the beds is achieved by oil ignitors, and bed material is removed by a vertical pipe that penetrates the air plenum. The flow rate of the bed material is controlled by a variable speed, water-cooled screw drive.

Fly ash from the bed passes through a cinder trap, which separates the coarse particles. The particles collected in the cinder trap are reinjected into the bed. Smaller particles are collected in the cyclone dust collection and are also reinjected into the bed. Particles escaping the cyclone dust collector are collected in the bag house.

Two serious setbacks to the plant were experienced, an undersized baghouse and erosion of convection tubes. The original baghouse could not handle the dust loading at full load and had to be replaced. All the convection tubes (450 total) had to be replaced but the erosion problem still exists. A cooperative effort is under way to study this problem further, and design changes are anticipated for satisfactory performance in the future. The overbed spreader-stoker feed system also required special attention, primarily because of poor fuel quality. A large quantity of rock has been delivered with the coal, resulting in frequent breakdown of the crushing and screening system.

The plant has been completely turned over to Georgetown University to operate as part of the steam utility system. A 2900-kW steam turbine is also being installed for cogeneration purposes.

East Stroudsburg anthracite culm Atmospheric Fluidized Bed Combustor [11]. Fluidyne Engineering Corp. has designed and erected a turnkey AFBC at the East Stroudsburg State College in Pennsylvania under a grant from DOE and the Commonwealth of Pennsylvania. The objective of the program is to demonstrate an AFBC fired with anthracite coal refuse (culm). Anthracite culm is a low-cost fuel that is plentiful in northeast Pennsylvania. The installation of the new AFBC will generate 6,800 to 18,000 kg/h steam.

Some of the unique features of the facility are: six eductor pneumatic fuel feeders that require no flow dividers; a valveless gravity flow recycle return system; a distributor grid, which allows spent bed material to pass down through it while being cooled by the incoming air; and a combination forced/natural circulation system. The fuel and sorbent will be transported in covered trucks from the preparation site, pneumatically conveyed to the bunkers inside

the boiler house and pneumatically fed to the boiler. The culm consumption is estimated to be approximately 11,600 tons per year.

The facility is now undergoing shakedown.

Wilkes-Barre Atmospheric Fluidized Bed Combustor [12]. The City of Wilkes-Barre, Pennsylvania, has installed an AFBC to burn a mixture of anthracite coal and culm having a heating value of approximately 1.4×10^7 J/kg. The contract for the facility, jointly funded by the city of Wilkes-Barre and DOE, was awarded in January 1983 to Keeler Boilers and Dorr-Oliver. Construction was completed in January 1984.

Some unique features of the Wilkes-Barre AFBC are:

- There is a complete water-cooled, seal-welded construction for the fluid bed containment.
- All steam generation surface in the bed is vertical (parallel to the gas flow), thus minimizing tube erosion.
- Turn-down is accomplished by simple on-off control of air to individual air sparge pipes.
- The design is modular to facilitate erection and final assembly.

Anthracite coal and culm are blended off-site and delivered in a mixed form. The fuel ranges from high quality anthracite culm to a mixture of low grade culm and pure anthracite coal. The bed height and excess air are varied to handle the wide range of fuels.

Initial shakedown and startup began in mid-February. Several hundred hours of operating time are expected to be logged in the summer of 1984.

Inactive/decommissioned FBC facilities. In the early 1980s, DOE shifted its emphasis from demonstration/pilot plant projects to more fundamental, small-scale programs. As a result, some of the earlier facilities have been shut down. Summary information on some inactive facilities is provided here to give additional background on the U.S. AFBC program.

Pope, Evans & Robbins designed, erected, and operated a 30-MW coal-fired multi-cell AFBC demonstration facility under contract to DOE [13]. The facility was located in the Rivesville Power Station of the Monongahela Power Company in Rivesville, West Virginia. The boiler was fabricated by the Foster Wheeler Corporation. Successful operation of the four cells in the boiler was demonstrated in August 1977. Features of the Rivesville AFBC included:

- Utility application, 30 MW(e), 136,200 kg/h steam,
- Four cells,
- Carbon burnup cell reinjection,
- Pneumatic feed,
- In-bed horizontal tube bundle-forced circulation, and
- Perforated plate and drilled-bolt air distributor.

The facility was plagued with numerous problems starting from the coal preparation and handling all the way to the particulate removal and flue gas exhaust system. Experience gained from the Rivesville facility was, however, valuable to the development of AFBC technology worldwide. In 1981, the Rivesville AFBC was decommissioned and dismantling begun.

A 0.8 m^2 AFBC module was installed at Alexandria, Virginia, in 1967 with the objective of developing a shop-fabricated, coal-fired industrial-packaged

AFBC [13]. The primary purpose for the unit was to provide data for the design of the 30-MW Rivesville AFBC and general performance data. In 1978, the unit was replaced by a new process development facility, designed as a flexible packaged coal-fired AFBC with a capacity of 2270 kg/h, 2.2 MPa steam. Studies included testing of eductor designs for fly ash reinjection, air distribution systems, bed light-off techniques, recycle tests, baghouse performance tests, bed level measurement, and experimental verification of AFBC computer models. The facility was decommissioned in 1983.

The Shamokin Area Industrial Corporation located in Shamokin, Pennsylvania, is rated at 9000 kg/h saturated steam [13,14]. The facility was sponsored by DOE, with Curtiss-Wright and Keeler Boilers and Dorr-Oliver as prime contractor and subcontractors, respectively. The objective was to demonstrate the combustion of anthracite culm in an AFBC and supply steam for industrial customers.

The plant was started up in August 1981, and testing continued until April 1983 for a total of 10,128 h. The initial operation revealed problems in the start-up and sustainment of combustion in the facility without an auxiliary burner system. Because of the low demand for steam (1300–1500 kg/h) the plant had to be run at much less than design conditions. As of April 1983, the plant has been shut down for an indefinite period because of low steam demand.

Pressurized Fluidized Bed Combustion Programs

Concurrent with AFBC programs, DOE, EPRI, and the Environmental Protection Agency (EPA) have been funding projects in PFBC. Combined cycle PFBC plants provide working fluids to drive both steam and gas turbines. The relatively high efficiency of the combined cycle PFBC systems makes them strong candidates for utility applications. In addition, for industrial applications, PFBC-packaged units offer a definite advantage in size compared to AFBC units. For these reasons, there has been a continuing effort in the United States in PFBC technology.

Table 2 describes some of the major PFBC facilities. A brief summary of these programs is contained in the following section.

International Energy Agency (IEA) Grimethorpe PFBC [15-17]. Under the auspices of IEA, the governments of the Federal Republic of Germany, the United Kingdom, and the United States agreed, in 1975, to co-fund an experimental PFBC test facility to carry out research. The PFBC test facility was built on a site adjoining a power station at the National Coal Board's Grimethorpe Colliery, South Yorkshire, England. The major objectives of the experimental program at Grimethorpe were to:

- build a PFBC experimental facility to study combustion, heat transfer, gas clean up, corrosion/erosion, and energy recovery;
- conduct tests over a wide range of operating conditions; and
- provide a broad engineering data base on the characteristics of different coals and sorbents in PFBC systems.

The PFBC is a water/steam-cooled coal-fired unit, 2 m × 2 m in cross section. The combustor is surrounded by an outer cooled vessel that provides pressure containment. The coal feed system is a Petrocarb fluidized bed lockhopper system which has been modified by the addition of a rotary feeder valve in each of the nine coal feed lines. The solids removal is from the bottom of the bed. The flue gas clean-up system consists of up to two stages of cyclone separators, with four cyclones in parallel in each stage. A tertiary gas clean-up

TABLE 2. Summary of the design specifications for the major U.S. PFBC facilities

Site	Bed dimensions/ feed points	Nominal bed conditions	Fuel	Sorbent	Heat-transfer/ working fluid
IEA PFBC at Grimethorpe	2 m x 2 m total 4 fuel injection points	Temp. = 790° - 900°C. Sup. Vel. = 0.75 - 3.7 m/s. Active bed ht. = 2 - 5 m. Freeboard ht. = 3 - 6 m. Pressure = 1200 kPa (abs) max. 10 - 100% excess air. No recycle.	Various coals. 1 - 5 wt % S. 0.64 cm x 0. Up to 17,000 kg/h. Underbed petro-carb injection from lockhopper.	Dolomite. 0.64 cm x 0. Up to 13,000 kg/h. Underbed petro-carb injection from lockhopper (mixed with coal).	Closed cycle/steam. Open cycle/flue gas. Steam P = 3000 kPa. Steam T = 440°C. Steam turbine on air compressor No gas turbine.
Curtiss-Wright PFBC SGT Pilot Plant	0.9 m diameter 1 fuel injection point	Temp. = 900°C. Sup. Vel. = 0.8 m/s. Active bed ht. = 4.9 m. Pressure = 510 - 680 kPa. Excess air. Fly ash recycle.	Bituminous coal. 3.2 wt % S. 0.32 cm x 0. 265 kg/h. Underbed pneumatic injection from lock- hopper (separate from coal).	Dolomite. 0.32 cm x 0. 45 kg/h. Underbed pneumatic injection from lock- hopper (separate from coal).	Once-through, air-cooled. 15% of cooling air and flue gas go to gas turbine. Remainder goes to quench tower and stack. Temps. to turbine 840° - 870°C.
Curtiss-Wright PFBC Combined-Cycle Pilot Plant	3.76 m diameter 12 fuel injection points	Temp. = 900°C. Sup. Vel. = 0.8 m/s. Active bed ht. = 4.9 m. Freeboard ht. = 4.6 m. Pressure = 690 kPa (abs) max. 30% - 35% excess air. Gravity fly ash recycle.	Bituminous coal. 3.2 wt % S. 0.32 cm x 0. 4090 kg/h. Underbed pneumatic injection from lockhopper.	Dolomite. 0.32 cm x 0. 1020 kg/h. Underbed pneumatic injection from lock- hopper (separate from coal).	Open cycle/air-flue gas. Closed cycle/steam (waste heat boiler). Steam P = 5500 kPa (abs). Steam T = 440°C. Compressor and power gas turbine. No steam turbine.
General Electric Materials Test PFB	0.31 m diameter 1 fuel injection point	Temp. = 950 °C. Sup. Vel. = 0.9 m/s. Active bed ht. = 1.6 m. Pressure = 1030 kPa (abs). 20% excess air. No recycle.	Bituminous coal. 60 kg/h. Underbed pneumatic injection from lockhopper.	Dolomite. 19 kg/h. Underbed pneumatic injection from lock- hopper (mixed with coal).	Closed cycle/water. Water cooled in external heat exchanger. In-bed exchanger duty = 0.23 MW. Low and high velocity materials test cascade. No gas or steam turbine.
New York University PFB	0.76 m diameter 1 fuel injection point	Temp. = 955°C max 840°C typ. Sup. Vel. = 2.4 m/s max 1.7 m/s typ. Active bed ht. = 1.4 m. Freeboard ht. = 4.8 m. Pressure = 1030 kPa (abs) max 810 kPa (abs) normal. 10 - 20% excess air. Recycle possible but not typically used.	Pittsburgh #8 and lignite. 0.64 cm x 0. 900 kg/h. Underbed pneumatic feed from lockhopper.	Dolomite or Alumina. Ca/S = 1 - 3. 0.20 cm x 0 (dolomite). 0.11 cm x 0 (alumina). In-bed gravity feed from lockhopper (separate from coal).	In-bed and waterwall cooling. No steam or gas turbines.

and turbine blade cascade are provided to study the corrosion/erosion of various turbine blade materials. Since hot commissioning of the unit in September 1980, the combustor has logged close to 4000 h on coal. The significant results to date are summarized below:

- Combustion efficiency of 98.5% has been obtained in the unit with recycle operation.
- Sulfur capture of 95% or better has been achieved, at a Calcium/Sulfur ratio of 2.5.
- Estimated efficiency of the primary cyclone is 95%; the secondary cyclone is 68%.
- Dust loading at the outlet of the tertiary gas clean-up cyclones is about 200 ppm. The alkali metal concentration in the flue gas at this location is 1-2 ppm.
- Large vertical temperature gradients, typically 40°C, have been observed in the bed. They appear to be greatest when the tube bundle design inhibits solids circulation.
- Severe erosion has occurred in the in-bed tube bundle, the cause of which has not been completely identified.

U.S. participation in the test program was scheduled to end in May 1984.

Curtiss-Wright PFBC Facility [17]. Curtiss-Wright is developing the air-cooled PFBC under contract to DOE. The two principal facilities involved in this program are (1) a development unit, called the small gas turbine (SGT) rig, operated since mid-1977, and (2) a 13 MW(e) pilot plant.

The SGT facility supplies heated air and flue gas to a small gas turbine and/or turbine blade cascade. The air used for fluidization and combustion is about one-third of the total mass flow in the combustor system. The "dirty" portion of the total flow is cleaned by means of a primary cyclone followed by three secondary cyclone gas clean-up systems before rejoining the other two-thirds of the mass flow, which is heated through vertically oriented finned bayonet heat exchanger tubes immersed in the bed. The input air to the two circuits is preheated to simulate gas turbine compressor discharge conditions.

The total operating hours on coal in the SGT is approximately 3500 h. The gas turbine was operated under load successfully for at least 1000 h. Tests in the SGT provided design data on combustor performance, heat exchanger performance, corrosion/erosion, turbine material performance, bed stability at part load and off-design conditions, and system reliability.

The SGT rig has been shut down and is being dismantled. Future plans are to relocate the facility at the DOE Morgantown Energy Technology Center.

Curtiss-Wright 13 MW(e) PFBC pilot plant [17]. In 1976, Curtiss-Wright was awarded a contract by DOE to construct the first fully integrated air-cooled PFBC pilot plant. As in the SGT, the air from the in-bed vertical cooling tubes is mixed with the combustion gas from the hot gas clean-up system. The hot gas clean-up train consists of three inertial-type separators to remove particulate matter prior to combining with the PFBC cooling air. The combined gas stream is first directed to a two-stage, axial flow compressor drive turbine and then to a single-stage, axial flow power turbine delivering 7.1 MW(e). The exhaust from the power turbine is directed to a waste heat boiler delivering the equivalent of 6 MW(e).

Construction of the pilot plant has been completed. Public Service Gas and Electric in New Jersey has submitted a proposal to operate the plant.

New York University bench scale PFBC [17,18]. New York University Aerospace and Energetics Laboratory has been involved in PFBC since 1976 and has constructed a bench-scale PFBC facility under contract to DOE. The objectives of the test program are to develop fundamental data and correlations for the fluid mechanics and combustion processes in PFBC and demonstrate the ability to burn low grade fuels under pressure.

The facility started its shakedown tests in September 1982, with bituminous coals. Subsequent testing has been with lignite. The combustor had logged 120 h on North Dakota lignite at the end of 1983. Preliminary results indicate that lignite agglomeration in the bed can be suppressed at higher pressures. In addition, an inert bed material (crushed alumina or sand) can be used as bed material when feeding lignite since sulfur is apparently captured by alkali compounds present in the lignite ash.

The facility is presently operating, and further testing on lignite is planned.

General Electric materials test facility [17]. The General Electric Company has designed and constructed a 0.31-m-diam PFBC test rig intended for long-term materials testing. The coal-burning, dolomite bed combustor is designed to produce off-gas which, after hot-gas cleanup by three cyclones in series, will have the temperature, composition, and dust loading of flue gas expected from a commercial-scale PFBC.

Materials testing is being funded by DOE and will complement earlier work conducted by Exxon, U.K. National Coal Board, and Curtiss-Wright. Tests will emphasize the corrosion/erosion effects and the durability of various turbine materials in a realistic PFBC environment.

Construction was completed in 1981. The facility has completed over 1000 h of corrosion/erosion verification. Long-term, steady state turbine material exposure testing will continue through 1985.

Circulating Fluidized Bed Combustion Programs

In recent years, CFBC has emerged as a promising candidate for industrial and utility coal-fired boilers. Compared to the conventional AFBC bubbling bed, the CFBC is characterized by high superficial gas velocity (45-90 m/s) and a high solid recirculation rate through the bed.

Lurgi, in the Federal Republic of Germany, first introduced the CFBC commercially in the early '70s for the chemical industry. Also during the '70s, the Ahlstrom Company in Finland started an active research and development program to commercialize CFBC for coal and other low grade fuels in boilers up to 45,500 kg/h steam. In the United States, Battelle-Columbus Laboratory in Ohio introduced the Multisolid Fluidized Bed Boiler concept in 1978, which is a type of CFBC.

Industrial CFBC coal-fired boilers up to 100 MW capacity are being marketed in the United States by Pyropower Corporation, Lurgi-Combustion Engineering USA, and Babcock & Wilcox USA - Studsvik Energiteknik AB, Sweden. Some of the design specifications for the two currently operating CFBCs are given in Table 3.

TABLE 3. Summary of the design specifications for the major U.S. CFBC facilities

Site	Bed dimensions/ feed points	Nominal bed conditions	Fuel	Sorbent	Heat-transfer/ working fluid
Pyroflow CFB at Bakersfield, California Gulf Oil	1 fuel injection point	Temp. = 840°C	Western sub-bituminous coal. 0.6 wt % S. 1.9 cm x 0. 2500 kg/h. Screw conveyor and rotary feeder into recycle duct to combustion chamber.	Limestone. Mean size 150 μ m. Ca/S = 2.2 Pneumatic injection into return duct to combustion chamber.	Steam generation for heavy oil recovery. Waterwall tubes in the combustion chamber, convection tubes in flue gas downstream from cyclone. Steam rate = 22,700 kg/h. Steam P = 17,300 kPa (abs). Saturated. 80% quality.
Conoco South Texas Multi-Solids FBC (CFBC)	1 fuel injection point	Temp. = 900°C. Sup. Vel. = 4.6 - 9.1 m/s. 15% excess air.	Laredo coal, Eagle Pass coal, Petroleum coke. 5 cm x 0. 0.6 - 7.1 wt % S. Gravity-pneumatic feed directly to the top of the combustor bed.	Limestone. 0.32 cm x 0. Ca/S = 4.5. Gravity-pneumatic feed directly to the top of the combustor bed.	Steam generation for tar sands recovery. Waterwall tubes in combustion chamber, convection tubes, immersed tubes in external heat exchanger. Steam rate = 22,700 - 27,400 kg/h. Steam P = 17,000 kPa (abs). 80% quality.

MAJOR TECHNICAL UNCERTAINTIES

Atmospheric Fluidized Bed Combustion

Although atmospheric fluidized beds are now commercially available for industrial applications, there are still important unresolved technical issues. This is especially true for large utility boilers. The most significant of these issues center on coal and sorbent feeding, sorbent utilization, carbon utilization, load control, erosion/corrosion, and scaling methods for design of large boilers.

Coal and sorbent feeding. Coal and sorbent feeding has probably been the most troublesome problem reported to date. Each of the two principal approaches, pneumatic underbed injection and overbed stoker feed, has unique difficulties that can strongly affect the overall boiler performance. The major advantage of underbed pneumatic feeding is that coal fines are introduced at the bottom of the bed so that carbon fines carryover is reduced. This in turn improves carbon utilization and reduces freeboard combustion. The major disadvantage is that pneumatic transport lines are highly susceptible to plugging and erosion. Thus, they require high maintenance and careful drying and sizing of the solids. This problem becomes especially severe for large beds.

Overbed stoker feeding eliminates the need for transport lines and multiple injection points, but it introduces two new problems; freeboard burning and segregation/defluidization. Freeboard burning results when the feed coal contains fines small enough to ignite and burn above the bed. This can be reduced by careful screening or washing of the raw feed coal, but then some other use or feeding method must be devised for the fines. Even if the raw coal is bottom screened, fines are always present to some degree due to attrition in the handling system. When the coal size becomes too large or heavy "rocks" (e.g., shale) are present, they begin to collect in the bottom of the bed to form a defluidized layer. Such a layer can severely inhibit bed solids circulation if it is allowed to accumulate.

The TVA pilot plant experience with coal and limestone feeding provides good illustrations of the types of problems encountered. Two good accounts of this experience are reported in Refs. 1 and 19.

Sorbent utilization. Sorbent utilization is a major concern in the United States because of the extensive resource of high sulfur coals. The amount of sorbent required to meet air emissions standards can have a significant effect on operating costs and the amount of solid wastes produced. To consistently reach the level of sulfur removal now required (i.e., 90% removal of the sulfur in the feed coal), AFBCs require Ca/S mole ratios of approximately 2.5, substantially higher than the ratio required by conventional flue gas desulfurization associated with pulverized boilers. This poor utilization is primarily a result of three factors: (1) attrition and elutriation of sorbent particles, (2) occlusion of the sorbent surface by solid reaction product (CaSO_4), and (3) incomplete sorbent calcination.

Attrition and elutriation ultimately determine the sorbent residence time in the combustion zone. Sorbent elutriation rates of 30% or higher are not unusual; thus, there has been heavy emphasis on the use of recycle of the elutriated fines. At best, however, recycle by itself will probably not allow reduction of the Ca/S mole ratio below 2. This is primarily because of the impervious CaSO_4 shell which forms on the outside of sorbent particles, preventing complete SO_2 penetration. Further occlusion results from the fact that CaSO_4

has a larger molar volume than CaO , and thus it tends to swell and plug the pores as the reaction proceeds. The result is that even sorbent particles which never elutriate from the bed usually reach less than 50% utilization [20]. This can be countered somewhat by using techniques such as hydration or grinding to "reactivate" the partially sulfated sorbent. [21].

Incomplete sorbent calcination occurs when sorbent particles elutriate rapidly after being injected. Experience at the TVA pilot plant demonstrates that more than 10% of the sorbent contained in the elutriated solids may be uncalcined, thus making it unavailable for capturing sulfur. Solutions to this problem have not been directly addressed as yet, although higher recycle rates will tend to mitigate the effect. Perhaps the most direct method of minimizing the escape of uncalcined sorbent would be to develop staged or compartmented beds in which the fresh sorbent is first exposed to regions of lower gas velocity until calcination can be completed.

Carbon utilization. Like sorbent utilization, carbon utilization is dominated by attrition and elutriation. Design features that tend to minimize these effects (e.g., low gas velocity, recycle of elutriated solids) tend to increase carbon utilization. However, the relationship between carbon utilization and the various design and operating parameters have still not been clearly elucidated. A recent ORNL review of the fluidized bed literature [22] has led us to conclude that the available data on carbon utilization are clearly inadequate to satisfactorily quantify these relationships, although certain trends are evident. These trends indicate that:

- once-through carbon burnup in AFBC is generally of the order of 90% to 92%,
- recycle of elutriated char can give a 2% to 3% increase in the overall carbon burnup,
- carbon burnup is coupled to coal particle size and superficial velocity such that there appears to be a minimum in the "carbon burnup vs coal particle size" curve,
- bituminous coal fines below 150 μm burn almost completely before they can be elutriated, and
- the combustor size, geometry, and internals have a strong influence on carbon burnup.

Several questions regarding carbon burnup remain unanswered. Some of the most important concern the relationship of bed depth, bed temperature, initial coal particle size, and recycle to carbon burnup. Quantitative characterization of freeboard combustion phenomena is also an important unresolved issue. We believe carefully controlled experiments are essential to develop a fundamental understanding of these parametric relationships.

One more point about carbon utilization is in order. Some utility spokesmen have expressed the concern that carbon utilization less than 99% will make AFBCs uneconomical for utility applications. We believe such blanket statements are premature. In the first place, it is not likely that such efficiencies can be achieved consistently in conventional AFBCs in the near future. Secondly, our own estimates [23] indicate that AFBC can still offer advantages over conventional pulverized coal-fired plants provided the technical issues affecting availability and boiler rating are resolved. The key deciding factor on whether or not to use AFBCs for electric power generation will be the expected cost of electricity, not the overall efficiency of fuel utilization.

Load control. As far as U.S. AFBCs are concerned, the principal constraint on load control is the narrow range of bed temperatures which allows efficient

sulfur capture with limestone, the preferred sorbent. There appears to be general agreement that sulfur capture is optimum at bed temperatures of $840^{\circ}\text{C} \pm 30^{\circ}\text{C}$. Excursions outside this range appear to reduce sorbent utilization, thus, making operation uneconomical. To circumvent this problem, two basic strategies have been utilized: bed slumping and velocity turndown.

Bed slumping depends on the compartmentalization of the fluidizing air distributor such that a portion of the boiler can be defluidized and essentially removed from service. Two important disadvantages of this method are that the boiler output tends to change in a stepwise fashion and that restarting slumped compartments can be difficult due to solids clinkering. A clear-cut test of bed slumping has not yet been made, but TVA is planning to evaluate the concept on the 20-MW pilot plant in the near future.

Small changes in the immersed heat transfer area can significantly change the bed heat balance because of the large in-bed heat transfer coefficients (e.g., $340 \text{ W/m}^2\text{C}$). Thus, turndown can be achieved by reducing the air velocity such that bed level and heat losses are reduced, requiring less coal feed to maintain operation in the critical temperature range. To be able to do this over a significant range requires a careful modeling of bed expansion and heat transfer characteristics. TVA reports successful short tests of this method in the 20-MW pilot plant. Stable operation was reportedly achieved at 85%, 70%, and 50% load [24]. Further testing is needed to establish consistent reliability.

Erosion/corrosion. Erosion and corrosion of immersed and convection surfaces have been anticipated because of the continuous exposure to moving solids and because of the alternately oxidizing and reducing atmosphere that can occur near fuel injection points. So far at least, these do not appear to have been serious problems at typical steam boiler temperatures. Unusual erosion problems, such as the convection tube erosion at Georgetown, appear to have resulted from designs that did not adequately incorporate available information.

As far as corrosion is concerned, careful selection of construction materials appears to be the key. Most difficulties have involved uncooled tube supports and coal-limestone feed nozzles [25]. Further work needs to be done to determine the best materials for these applications. Long term performance testing of materials for heat transfer surfaces remains an area where information is not available; however, significant problems are not expected up to typical steam boiler temperatures.

Scale-up. From a fundamental standpoint, the relationships between bed parameters and gas-solids circulation and mixing are poorly understood. This has caused significant difficulties in the development of scaling laws, and no method is currently available for confidently predicting large-scale bed behavior from pilot-scale data. Development has, instead, had to depend on a costly stepwise approach of building larger and larger test facilities.

Pressurized Fluidized Bed Combustion

Technical uncertainties in PFBC development differ from AFBC uncertainties in four primary areas:

1. Erosion/corrosion of the gas turbine blades,
2. Fuel and sorbent feeding against high pressure,
3. Load control, and
4. Erosion/corrosion of bed internals.

Erosion/corrosion of the gas turbine blades is primarily a concern for combined cycle PFBCs that have exhaust gas temperatures of approximately 870°C going to the gas turbine. The chief problem here is to develop high-temperature, high-pressure gas clean-up devices for particulate removal. Hot-gas cleanup efforts to date have considered cyclones, granular bed filters, fabric filters, electrostatic precipitators, and acoustic agglomeration for particulate control and chemical and physical adsorption for alkali control. Ultimately, an economic solution to the hot-gas cleanup problem will be the key to commercialization of combined cycle PFBC.

Most current experimental and conceptual designs utilize pressurized lockhoppers for feeding coal and limestone. This method has a serious drawback because of the work that must be expended to compress the lockhopper gas and the cost and complexity of such equipment. Other methods have been suggested to overcome this difficulty, most notably, feeders with some sort of mechanical sealing devices and slurry feeders. Tests sponsored by DOE and the Coal Utilization Research Laboratory in Leatherhead, England [26] indicated that the coal-water slurry may be a viable feeding medium.

Load control is not as serious a problem as it is for AFBC. The main reason for this is that the temperature constraint for acceptable sulfur capture is less severe with dolomite, allowing operation over a broader temperature range, between 790° and 980°C. PFBCs also usually operate with much deeper beds than AFBCs, making it easier to use velocity turndown for load control.

The Grimethorpe facility has exhibited severe erosion of the in-bed tubes [27]. The reasons for this erosion are still being investigated, but we believe the most likely hypothesis is that an unusual solids circulation pattern developed which greatly enhanced the severity of the solids-tube impaction. The cause of this unusual circulation pattern is probably connected with the specific geometry and orientation of the tube bundle experiencing most of the erosion.

Circulating Fluidized Bed Combustion

United States experience with CFBCs is very limited. There are only two operating units of significant size [28,29]. CFBCs appear to offer distinct advantages in load control and boiler size. However, three aspects of the CFBC design have resulted in some concern: the high combustion gas velocities, the high solids circulation rates, and the lack of internal heat transfer surfaces in the combustor. High velocities pose the potential for erosion problems. In this case, it would be erosion of the refractory-lined walls in the flue gas ducting and hot cyclone, since there are no internal tubes in the high velocity section. High solids circulation rates increase the required hot cyclone size. Both high velocity and high solids loading also greatly increase the overall pressure drop (and, thus, fan requirements).

The lack of internal heat transfer surfaces in the combustor may pose the biggest problem for scale-up, especially for utility size boilers. Since the percentage of heat removed from the combustion zone diminishes as the combustor size increases (i.e., the surface-to-volume ratio for the combustion zone changes as the inverse of the diameter), this may constrain CFBCs to some maximum practical size, unless some means can be found for introducing internal cooling surfaces without the risk of erosion.

FUTURE OUTLOOK

The future outlook for FBC technology in the United States is encouraging. Both utilities and industry will continue to rely more heavily on coal combustion. As the potential advantages of FBC are demonstrated and the reliability risks diminish with experience, FBC will compete favorably in both electric power and industrial process heat markets.

Atmospheric/Circulating Fluidized Bed Combustion

FBC is already enjoying a significant market growth in industrial process heat as indicated by the number of AFBC/CFBC boiler contracts shown in Table 4. Table 4 also illustrates the tremendous fuel flexibility of the technology and the substantial number of manufacturers in the market place. The shift from the use of fuel oil or natural gas to coal in the United States can offer significant long-term economic advantages, but involves a major short-term capital investment. Thus, the rate of growth in the use of AFBC/CFBC technology in industry has been modest but should accelerate with time.

Utility application of AFBC has been promoted primarily by TVA and EPRI to date. A 160 MW(e) demonstration unit is planned by TVA, EPRI, Duke Power, and the Commonwealth of Kentucky at TVA's Shawnee steam plant (site of the TVA/EPRI 20 MW pilot plant). Completion and start-up of the unit are scheduled for 1989 as indicated in Table 5.

Two other utility projects are under consideration in the United States. Northern States Power proposes to convert an existing 100 MW(e) pulverized coal boiler to AFBC and Colorado-Ute proposes a demonstration CFBC of 100 MW(e) to replace existing stoker-fired boilers that will be retired [30]. EPRI is participating in design studies with both utilities, and plans are progressing toward project completion dates in the late 1980's. Summary data on these units are also shown in Table 5.

TABLE 5. Proposed utility FBC demonstration plants

	TVA	Northern States Power	Colorado-Ute
Location	Paducah, Ky.	Minneapolis, Minn.	Nucla, Colo.
Size, MW(e)	160	125	110
FBC type	AFBC	AFBC	CFBC
Scope	Add-on boiler	Boiler conversion & T/G	Add-on boiler
Coal	High S	Low S	Low S, high ash
bituminous	sub-bituminous	bituminous	
Start-up	1989	1987	1988
Steam conditions	Reheat	No reheat	No reheat
Feed system	Underbed or	Overbed	In-bed
overbed			

TABLE 4. Industrial boiler contracts in the U.S.¹

Manufacturer	Type	Number of units			Fuel(s)
		15,000 (kg stm/h)	15,000 — 46,000 (kg stm/h)	46,000 (kg stm/h)	
Babcock & Wilcox	AFBC	3		1	coal
Combustion Engineering	AFBC	2			coal
Dedert	AFBC	2			wood, coal
Deborah	CFBC	1			waste oil, tires
Dorr-Oliver/Keeler	AFBC	1	5		culm, other
Energy Products of Idaho	AFBC	18	1	1	wood
Energy Resources	AFBC	1			coal
Fluidized Combustion Contr.	AFBC		1		coal
Fluidyne	AFBC	2			multi
Foster Wheeler	AFBC		6	3	CO, natural gas
Johnston Boiler	AFBC	8			coal, process waste, nat. gas wood, oil
Pyropower	CFBC	2		1	coal
Struthers Wells	CFBC	2			coal, lignite, pet. coke
Wormser Grate	AFBC	1	1		coal
York-Shipley	AFBC	16	1		wood, poultry litter
Total		59	15	6	
(+ 31 Unidentified)					

¹Tabulation by Babcock & Wilcox in August 1983.

Pressurized Fluidized Bed Combustion

The general concept of an industrial-packaged PFBC offers advantages in that (1) packaged boilers are substantially less expensive than field-erected units of the same capacity and (2) pressurizing the boiler results in a significant size reduction potentially allowing packaged units to be built in larger unit sizes.

An industrial-packaged PFBC concept suggested by ORNL* would generate 68,000 kg/h steam in a 3.7-m-diam boiler vessel that could be shipped by rail or barge [31-33]. The concept is based on a 0.35 MPa pressure maintained by a single stage exhaust, gas-driven turbocharger designed to provide compressed air only (no net electrical/mechanical energy).

The industrial-packaged PFBC has not progressed beyond the conceptual design stage in the United States but development of such a concept in the foreseeable future is a reasonable expectation with continued growth of the market for coal combustion technology in industrial process heat applications.

A somewhat similar approach is being taken by EPRI* in its development emphasis on turbocharged, shop-fabricated, barge transportable PFBC units for utility application in unit sizes of 100 to 250 MW(e). Again no net power is extracted from the turbocharger, which functions at lower temperature and with lower technical risk. This concept was recommended by Brown-Boveri in 1982 as a near-term commercial alternative to the more familiar high-pressure combined-cycle PFBC concept in an assessment for EPRI. Subsequent studies have been carried out by several turbine/boiler manufacturers. A prominent study by General Electric, Babcock & Wilcox, and Florida Power and Light (FP&L) resulted in consideration of repowering an 80-MW(e) unit at the FP&L Palatka plant.

The more advanced combined-cycle PFBC concept remains a viable option but appears to be farther in the future. Circulating-bed technology is also being considered along with conventional bubbling-beds in a current EPRI-sponsored study of turbocharged PFBC design alternatives and cost estimates by Brown-Boveri, Fluor, Combustion Engineering, Foster Wheeler, Lurgi, and Research Cottrell.

*Both the ORNL and EPRI concepts described herein are derived in large part from the Supercharged PFBC concept originated by A. P. Fraas, G. Samuels, and M. E. Lackey of ORNL in 1976 [34].

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